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FINAL REPORT

Acoustic Emission and Mechanical Properties of Snow Related to Avalanche Release

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MARCH, 1977

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The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The project was concerned with evaluation of the physical and mechanical processes associated with snow avalanche initiation. Four separate tasks were involved in this effort: (1) a stress wave study to evaluate the response of snow to transient loads, (2) a slope stability investigation to determine the effectiveness of boundary conditions on slope stability, (3) a material constitutive representation to evaluate material properties for loads characteristically found in snow slopes, and (4) an acoustic emission (Cont.)

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study to study the process of slab release.

Considerable progress was achieved in all portions of the project. An electromagnetic stress wave generator was successfully constructed and tested, and tests are now being carried out with this instrument. An equivalent linear viscoelastic model has been formulated for snow for densities, temperatures, and load conditions characteristic of alpine snow slopes. The acoustic emission field study is still gathering data, and a predictable pattern of acoustic emissions appears to be related to the process of fracture and avalanche initiation. The results of this one year project have been reported in seven publications and symposium presentations.

KEY WORDS:

Acoustic Emission
Avalanche Release
Snow Properties
Snow Avalanche Initiation
Snow Slopes
Alpine Snow Slopes

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1. INTRODUCTION

The research reported herein involves a coordinated study plan to (1) develop a better understanding of the mechanisms leading to snow avalanche initiation, (2) the development of constitutive laws for analyzing snow slopes, and (3) evaluation of the feasibility of acoustic emission technology for detecting slope instability. In addition to the applicability of this project to avalanche mechanics, the project results also have significant military relevance. This will be discussed in detail in a separate section.

Briefly, the project, which was jointly supported by ARO-D, NSF, and the USFS Rocky Mountain Experiment Station, was divided into four separate sub-tasks. These were:

1. Stress wave laboratory study
2. Slope stability
3. Material constitutive representation
4. Field program and acoustic emission

These projects in some instances represented a continuation of work supported by an earlier grant (No. DA-ARO-D-31-124-73-G175), and some parts of the work involved entirely new problems. The acoustic emission task was begun under the previous grant and was also supported under the grant reported here. This portion of the task required an extensive field investigation which could not rationally be concluded in a single two-year period. The material characterization study was intended to supplement results achieved in the earlier grant and to formulate a constitutive law readily usuable for stress analysis of snow slopes. The other two portions of the project, the stress wave and slope stability studies, relate to problems not considered in the previous task.

2. SUMMARY OF RESEARCH RESULTS

(a) Stress Wave Laboratory Study

This particular investigative topic was chosen because of the questions surrounding the many transient conditions which lead to avalanche initiation. Among the avalanche researchers in the field, there is considerable disagreement over the effectiveness of explosives in causing avalanches. Topics of discussion have included (1) what speed of the explosive is optimum, (2) what size of explosive is deemed necessary to give assurances of obtaining reliable results, (3) what is the optimum placement of the explosive, i.e., above, in, or below the snowpack.

In addition to the avalanche-related topics, the Army is also concerned about such questions as oversnow vehicle travel and terminal ballistics. The nature of these two problems are addressed directly by this particular project.

All of the above-mentioned occurrences (explosives, vehicles, terminal ballistics) produce stress waves of varying intensity. As a consequence, a detailed study of the response of snow to stress waves would help to obtain answers to these questions.

A laboratory study was chosen rather than a field study, since it was felt a laboratory investigation would allow better control of certain important experimental parameters, such as temperature, density, snow type, stress wave intensity, etc. However, it was also felt that a complete study would eventually require a field investigation, although this was beyond the scope of the project reported here.

An electronmagnetic stress wave generator was designed and constructed at MSU, and a schematic of the circuit is illustrated in Figure 1. Basically, two low inductance capacitors are used to store electrical energy at voltages as high as 15,000 volts. A spark-gap trigger is then used to close the circuit and discharge the capacitors. A very high current (as high as 120,000 amps) is generated during the discharge. By directing this current in opposite directions along opposite sides of a thin insulating plate, a very large repelling electromagnetic force can be generated in an extremely short period of time. Maximum pressures can be produced in as little as 1 microsecond, which is faster than the fastest explosives commercially available. For specimen with a 3" x 3" cross sections, complete destruction was achieved with pressure as high as 55 bars.

The advantages of this system include: (1) low scatter (characteristically less than 3 percent, as compared to more than 15 percent with explosives), (2) ease of operation, (3) complete flexibility in controlling maximum pressure and rate of loading, (4) quick turn-around time, (5) no necessity of dealing with dangerous explosives. Some disadvantages include: (1) electrical noise produced by the system, and (2) a high voltage danger which requires additional safety features. The electromagnetic noise, however, is significant for only about 10 microseconds during the trigger discharge. The system is currently operational and has been found to perform satisfactorily.

A microwave horn is used to measure the motion of the free end of the test specimen. The system employs an interferometer technique to measure the phase change between the emitted wave and the wave which is reflected from the specimen free surface. With this system, motions as low as 10^{-5} meters can be detected. The pressures generated by the stress wave generator are calculated by evaluating data gathered from the Rogowski coil. In addition, an acoustic emission transducer is planned for use in evaluating acoustic emissions produced by the stress wave.

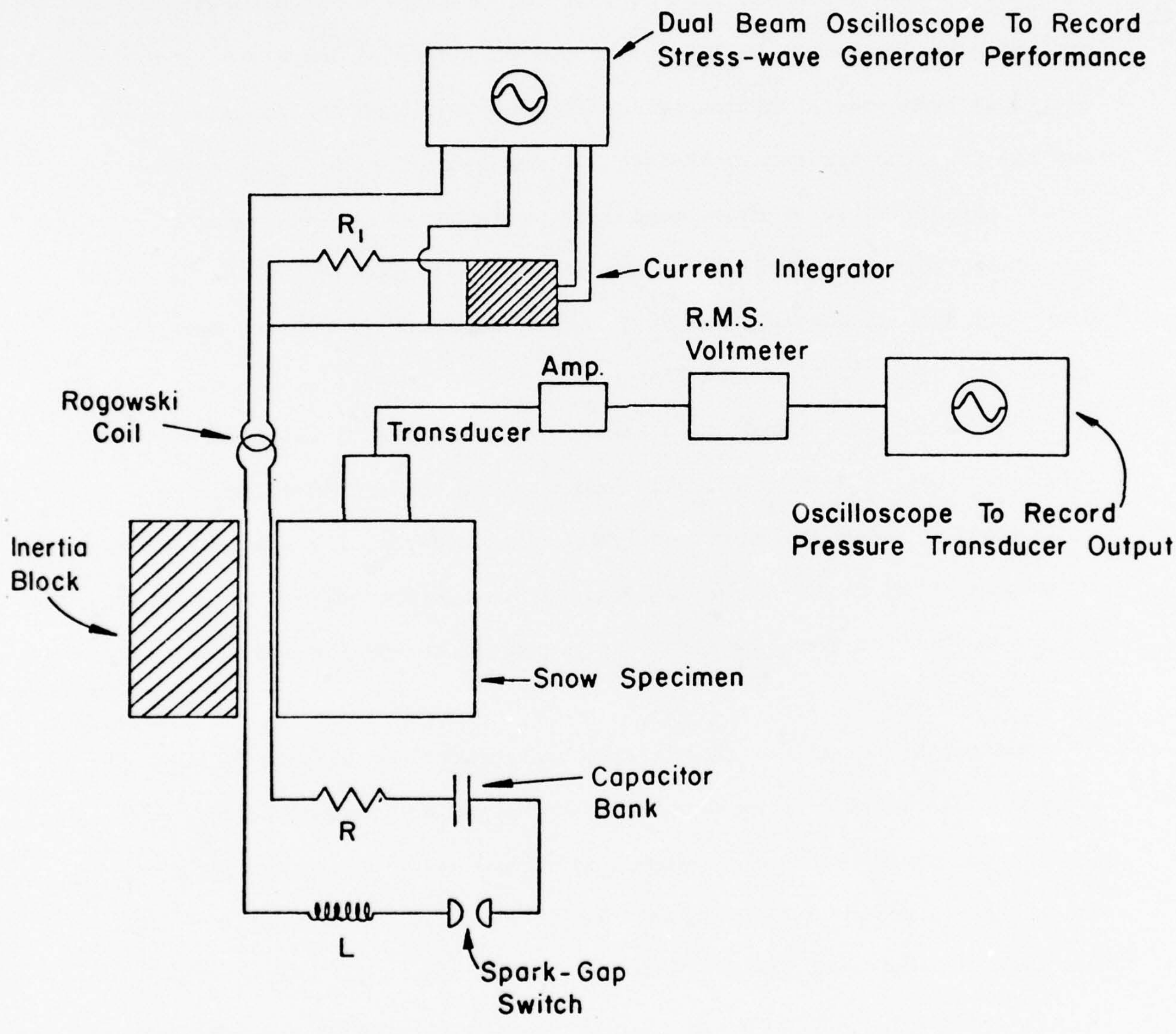

FIGURE 1

SCHEMATIC OF EXPERIMENTAL SETUP FOR STRESS-WAVE STUDY

Simultaneously with the equipment development, we have proceeded to formulate a dynamic constitutive law to predict the response of the material to high intensity shock waves. Since shock waves generated by explosives and terminal ballistics result with massive amounts of volumetric deformation, a volumetric constitutive equation was formulated and was found to accurately predict the response of snow to pressure loads characteristic of those generated by explosives. The result of the constitutive law have been compared with data supplied by the U. S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, with excellent results.

At present, not enough data has been collected with the stress wave generator to make a full evaluation of the constitutive law. In addition, planned improvements in the present constitutive law to enable this equation to handle a more general load situation has not yet been finished. Work on these two items is presently moving forward at a satisfactory rate.

The project described in the above paragraphs was originally planned and proposed to the Army as a two-year grant, since it was felt that the fabrication of the equipment, execution of an extensive testing program, and the development of the dynamic constitutive law would require a full two years to complete. ARO-D, however, has funded the research project at a reduced level for only one year, since the feeling by the Army was not in favor of a contract supported jointly by three separate Federal agencies (ARO-D, NSF, USFS).

In view of the reduced period of support, the full objectives of the proposed project could not successfully be completed in the one year period. However, the experimental equipment has been developed and a constitutive law has been formulated.

(b) Slope Stability Investigation

It is generally recognized that the release of a snow avalanche must be preceeded by a weakening of the boundaries of the snowpack in some manner. Attention is most often directed to the existence of weak layers that define the bottom or running surface of the avalanche. However, for small avalanches the flank, toe and crown boundaries must also be in a critical state to release. The crown and toe regions are loaded in tension and compression respectively. The flanks are loaded in tension and shear (based upon fracture evidence). The side boundary conditions play a progressively less significant role in comparison to the bottom weak layer as the size of the snow slope is increased.

Work has been initiated to investigate the question of how weak the bottom surface must become and how important the side boundaries are in snow release. To date no evaluation has been directed to strength of the flank boundaries primarily because of the difficulty in simulating the failure.

For the toe and crown boundaries a developed failure theory by Brown (1976) can be applied directly to evaluation of when failure is eminant based upon creep rate and total creep. To substantiate this hypothesis a number of tests were performed on slopes of angles greater than 35° to simulate toe and crown failure. Two parallel trenches were dug a meter apart on the fall line of the slopes, thus forming a free standing beam of snowpack. The beam of 20 m length or so was split in the middle, so that 9 m beams extended upward and downward. Plywood plates were then inserted successively downslope behind a sawcut to simulate a weak layer. What was formed was a 1m x 1m cross-sectioned beam on a measureable weak base that was extended until the tow region failed. Upon completing the compression test the procedure was duplicated for the tensile beam upslope. During the test period friction of the plywood plates was measured by tilting the plates while supporting a snow block. A total of 17 beam tests were completed during the winter of '75-'76 with complete specification of average density, snow stratification, snow and air temperatures, etc.

A second winter of beam testing was scheduled and is needed in order to complete the testing program. However, with the truncation of the ARO-D funding to one year instead of two, the second year of testing is delayed, as is numerical evaluation in order to verify the failure theory. Once a failure theory is verified then it can be applied to actual avalanche regions with confidence. Thus if crown, toe and running surface models can be developed analytically, based upon controlled experiment verification, then evaluation of flank strength may be possible. The intent of the entire research program, to assess the effect of boundary constraints on avalanche release, is then subject to review to appraise what constitutes the weakest element. Knowledge of the weakest element has current application in other research areas, such as acoustic monitoring of snow slopes, as a means of hazard control.

A second series of tests were run to evaluate the strength reduction of snow in order to have a free standing column fail. An equilateral triangle of snow, 2m on a side, was cut from sloping snowpack of nominal depth 2m. Starting at the three corners the free standing column of snow was undercut at different rates until the block failed in shear and slid downslope. Results of this investigation indicate the significant reducin running surface strength that is required in order for initial snow-pack release.

Brown, R. L., 1976. A fracture criterion for snow, Symposium on Applied Glaciology, Cambridge, England, Sept. 1976. Proceedings in press.

(c) Snow Mechanical Properties Investigation

Upon review of the literature pertaining to mechanical properties of snow, two conclusions can be made. First, generally, snow material properties are most often reported by giving equivalent values of Young's Modulus, E, Poisson's ratio, V, and secondary creep rate, η. Second, these material coefficients are reported for applied loads greatly in excess of any to be expected in snowpack of depths of the order of one or two meters. The deficiency of reporting elastic constants, is that snow is not elastic, but rather viscoelastic, meaning that material response is time dependent as well as load dependent. This basic dependence, plus nonlinearity of the material make it difficult to extrapolate small loading coefficients from reported large loading coefficient curves. Additionally, any analytical consideration of response to transient loading or short time loading is precluded because short-time material response coefficients are not measured or reported.

Thus the intent in this snow mechanical properties investigation is to first recognize snow as a viscoelastic material, and second to carry out measurements at low creep rates corresponding to known rates in sloping snow pack. It is recognized also that this must be an ongoing project since ultimately hundreds of tests must be made to evaluate the many aspects of a complete material evaluation.

Under ARO-D funding a start was made in material evaluation, and one years' work of an originally scheduled two year program was completed. A total of 63 tests were performed at creep rates corresponding to tension, compression and shear loading in snow ranging in density between 2000 Nm^{-3} and 3500 Nm^{-3} and at temperatures of -5, -10, -15°C.

In testing at low creep rates a fundamental difficulty arises. If one allows the test to run for several days, so that measurable deformations occur, the snow specimen, unless adequately protected will change properties and distort the results. The alternative is to use high sensitivity electronic equipment so that accurate measurements can be made at early times in the test. Since no known technology exists on protecting snow from exposed surface metamorphism wihtout disturbing sample response, the approach of designing and using sensitive electronic equipment was taken. A highly stabilized and low noise carrier amplifier was designed and built to drive an LVDT Transducer for axial and shear measurements. For the far more difficult measurement of transverse displacement, a low noise D. C. powered four arm bridge circuit with strain gages mounted on a flexible stainless steel beam was built. This system, although delicate, has sufficient sensitivity to detect transverse deformation from which strain rates of order 10^{-8} sec^{-1} can be computed. Equipment development and checkout required four months duration.

During this time a computer code was written to facilitate computation of material coefficients from the experimental curves. Recognizing the basic nonlinearity of snow, the plan is to pseudo-linearize the coefficients. This is done by determining a set of material coefficients, and to within some specified accuracy, say $\pm 20\%$, indicating the range of strain rates and snow type for which these coefficient apply.

Even though ARO-D funding of this project was terminated after one of a two year program, the project is continuing, and a compliation of results will be published. It is anticipated that in a remaining year duration a large number of additional tests will be run. This will provide as complete a description of snow in creep, as is needed with current technological demands for material description.

(d) Acoustic Emission Study

This section of the report is concerned with research effort devoted to evaluation of acoustic emissions in the deformation and failure processes in snow. This investigation was divided into a laboratory investigation to study the fundamental nature of acoustic emissions and a field investigation to observe how acoustic emissions are related to the failure of snow slopes. In the field the investigation was expanded to include observations made in the seismic frequency band as well as in the ultrasonic range. Generally, all our findings obtained to date have been published in scientific papers (see Section 5), with the salient points of this research summarized here.

In our laboratory study, it was found that the ultrasonic activity eminating from snow was associated with the fracture of grain bonds. Spectral analysis of these ultrasonic emissions indicates that the maximum acoustic energy from a typical event occurs in the region of 120 kHz. Further the acoustic response is related to the particular stress rate to which the snow is subjected.

Considering the patterned response that was observed when snow was subjected to various deformation histories it was hypothesized that the acoustic activity represented an important variable in the deformation of snow. This in turn led us to the formulation of a constitutive law in which the acoustic activity is integrated into the flow law as a fundamental variable. In our initial work this theory was presented as essentially heuristic and is currently being developed into a comprehensive constitutive law. Of considerable importance in our work was the observation that snow also exhibited a marked Kaiser effect. This discovery gave us the ability to evaluate the stress state to which snow has been previously subjected. Although at present this particular investigation has been confined to the laboratory, it shows great promise in terms of field application.

It was the purpose of the laboratory program to study the acoustic emmissions from snow in order that we might anticipate what we might find in our field investigations. The laboratory study also allowed us to perfect our techniques for our field program. With this preparation, an avalanche path was selected in the Bridger Range of Montana and monitoring of this path was carried out during three winters beginning with the winter season of 1974-75.

During the first year of our field investigation a major slab avalanche occurred in the slide path being observed. The second field season (1975-76) saw very little slide activity in the entire range with no slide running in the selected path. The third season which is currently underway has to date produced one major slide cycle. During the current season monitoring at the time of avalanche release was confined strictly to low frequency signals.

Results leading up to the first winters slide showed a number of interesting, yet unexpected, results concerning acoustic emissions preceeding avalanches. The most significant result observed was that for sometime prior to the avalanche release a general decrease in the acoustic activity occurred. This observed pattern was contrary to what was expected. It was also observed that periods of stability were associated with periods of increase emissions, prior to the time the snowpack became isothermal at 0°C.

In light of these results it appears that an increase in acoustic activity in a cold snow pack represents a strengthening of the snow. This strengthening is probably effected by an adjustment in the geometric arrangement of snow grains to accommodate increases in the state of stress in the slope. As has been demonstrated in the laboratory, subjecting snow to stress and loading rates below the fracture rate often increases the fracture toughness of the material relative to subsequent loadings. Conversely, periods of low acoustic activity indicate that little rearrangement of the grain structure is taking place in the snow. This implies that little strengthening of the snow is taking place, thus making the slope more susceptible to fracture at lower stresses or loading rates.

As the field investigation into acoustic emissions was initially conceived the primary emphasis was to be placed in observations of ultrasonic emissions. In the course of the first field season it became obvious that some means of relating ultrasonic noise to major shifts in the snowpack was required. As a means of achieving this a portable microearthquake recorder was installed at the field site in the first year of the investigation. With the installation of this instrument it was possible to detect major events occurring in the snow.

Through careful observation we were able to identify the characteristic seismic signals associated with various types of avalanches, cornice fall and internal fracture of the snow-pack. In the case of this latter type of signal we are able to obtain some information on the fracture susceptibility of mountain snowpacks. Consideration of this type of signal also gives some indication of the stability of the slope.

Due to the problems of servicing a microearthquake recorder in a mountain environment a radio telemetry system was installed. Using low power electronics continous remote sensing of the slide path is now taking place.

Under our current research program we have successfully investigated acoustic emissions both in the laboratory and in the field. In our field studies we have extended our research to include signals emitted not only in the ultrasonic region of the frequency spectrum but also in the seismic region.

The results of the field investigation indicate that the acoustic emission method is a viable technique for monitoring the stability of mountain snowpacks. Further work in this field may also lead to a viable method of predicting delayed action avalanches. The most important current consideration is the establishment of a data base from which to make stability predictions.

3. MILITARY RELEVANCE

The military undoubtedly must consider operations in alpine or snow-covered terrain to be part of its overall operations program. In alpine areas, snow avalanches pose a definite threat to personnel and equipment. Beyond that, mobility on snow-covered terrain is also of concern to military operations, since movement of equipment is hampered by increasing snow depths. In addition, terminal ballistics in snow is an area of study which merits further study. The present research study results bear potential application to these problems as well as to others.

As an example of a possible application to military problems, consider the topic of terminal ballistics. Medium density snow has been found to be an extremely effective material for stopping rifle fire and for dissipating energy generated by cannon fire. Mechanisms involved in energy absorption and dissipation in snow is not fully understood. However, the stress wave work reported here has a definite potential of expanding knowledge in this particular area.

The applicability of acoustic emission work to military problems holds great promise. For example, while the work done here is concerned with snow, the equipment and knowledge developed in this project can find applications to such activities as monitoring loads on ice piers in the Antarctica, evaluating the load-carrying capacity of ice sheets, or even detection of recent operations on ice sheets by means of the Kaiser effect.

The work on the material representation may be used to directly study the load-carrying capacity and the deformation of non-homogeneous layered snow under the effect of snow vehicles. Results of such studies could be interpreted in terms of vehicle power requirements and efficiency factors for various types of propulsion systems.

The above discussion does not exhaust the possibilities of the work covered in this grant, but it does demonstrate that, while the project was immediately concerned with the avalanche problem, it is also relevant to other military concerns.

4. CONTINUING RESEARCH

As indicated in the preceding sections, work is either continuing on research covered in the project or has begun as indicated by the project results.

In particular, the one year funding period was found to be inadequate for completion of the stress wave study and the material characterization study, and therefore work is continuing on these problems. In particular a more exact volumetric constitutive law is under development to characterize response of snow to high rates of loading.

Additional areas of interest are emerging as possible study programs in the future, although presently no funding has been sought. Included in this is a study on the process of heat conduction in snow, whereby the relative roles of solid heat conduction, convection, sublimation, and diffusion are investigated. This study hopefully will lead to more exact knowledge of temperature gradient metamorphism.

5. PUBLICATIONS PRODUCED BY RESEARCH PROJECT

The following is a chronological listing of the publications which at least partially may be attributed to the efforts of the research project.

St. Lawrence, W., and Bradley C. C., Spontaneous Fracture Initiation in Mountain Snow Packs, Proceedings of the International Symposium on Applied Glaciology, Cambridge, England , September, 1976.

St. Lawrence, W., Acoustic Emissions in the Investigation of Avalanches, 29th Canadian Geotechnical Conference on Slope Stability, Vancouver, B. C., Canada, October, 1976.

Brown, R. L., A Volumetric Constitutive Law for Snow Subjected to Large Strains and Strain Rates, (forthcoming as a USA-CRREL Report).

Brown, R. L., Application of a Dynamic Constitutive Law to Shock Waves in Snow, (forthcoming as a USA-CRREL report).

Brown, R. L., High Rate Volumetric Loading of Snow, invited paper, ISTVS Meeting on Impact of Snow in Transportation, Hanover, New Hampshire, February 23-25, 1977.

St. Lawrence, W., The Role of Acoustic Emission in Snow Mechanics, invited paper, ISTVS Meeting on Impact of Snow on Transportation, Hanover, New Hampshire, February 23-25, 1977.

St. Lawrence, W., Contributor on Passive Seismic and Acoustic Techniques in Glaciology, Encyclopedia of Ice and Snow, Ed. Fairbridge, R. W., Dowden, Hutchinson, and Ross Inc. To be published 1977.

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